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ABSTRACT

Quadratic, multi-order diffractive lenses have been designed, fabricated, and demonstrated for the MMW-THz region, with the capability of focusing harmonic wavelengths on to a common focal point. Design wavelength and harmonic spacing can be chosen as design parameters, allowing great flexibility in lens design. Simulations were carried out to determine lens parameters and performance. These lenses reduce both spherical and chromatic aberrations at harmonic wavelengths, and are thinner and lighter than traditional refractive elements. This lens type is potentially useful to sensor fusion architectures.

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Design of Multi-Order Diffractive THz Lenses

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Abstract— **Quadratic, multi-order diffractive lenses have been designed, fabricated, and demonstrated for the MMW-THz region, with the capability of focusing harmonic wavelengths on to a common focal point. Design wavelength and harmonic spacing can be chosen as design parameters, allowing great flexibility in lens design. Simulations were carried out to determine lens parameters and performance. These lenses reduce both spherical and chromatic aberrations at harmonic wavelengths, and are thinner and lighter than traditional refractive elements. This lens type is potentially useful to sensor fusion architectures.**

I. Introduction And Background

Current THz lenses are typically refractive elements with at least one spherical surface. These lenses are thick and have several inherent optical aberrations. The search for a thinner lens, with useful bandwidth is an ongoing quest. Diffractive Fresnel lenses and zone plate lenses have been analyzed as one possible solution, but they have been first order lenses and are heavily wavelength dependent [1,2,3]. Here we investigate the use of multi-order diffractive (MOD) Fresnel lenses. These lenses differ from the traditional diffractive lens in that the focused wavelength region can be tuned and modified as a design parameter by selecting the integral order (p) in Eq. 1 below [4]. One can see that when the design focus, and wavelength dependent focus are equivalent, several wavelengths will focus on the same spot. Then as the "zone" (m) increases, as shown in Fig. 1, the focused wavelength harmonic will be incremented. The focused wavelength (λ) will then be equivalent to the design wavelength (λo) when m = p.

$$F(\lambda) = \frac{p\lambda_o F_o}{m\lambda} \quad (1)$$

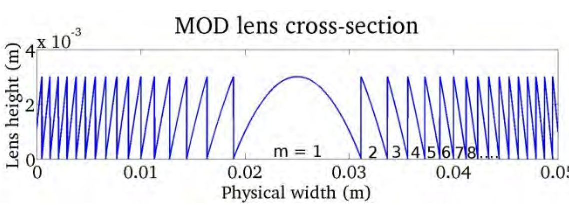

Figure 1. Cross section of MOD diffractive lens.

MOD elements have been studied in the IR and visible regions and have shown to greatly reduce lens height profile, while supporting greater flexibility in lens design. However fabrication in the IR and visible regions is difficult, because of the extremely small features of the lens. The physical steps created on the optical surface are too close in size to the wavelengths being used. This lends itself to poor optical quality, due to a rough surface. In the MMW-THz regions the longer wavelengths allow for larger feature sizes on the optical surface. This makes the fabrication process easier and more accurate, thereby improving optical quality. A CNC lathe can be used to carve the lens out of standard THz materials such as high-density polyethylene or Teflon, both of which work well in the MMW-THz region [3]. We show in this work that MOD lenses can demonstrate excellent optical focusing with reduced aberration compared to their spherical refractive counterparts. A parabolic refractive lens has also been fabricated from Teflon and will be used as a benchmark for the MOD lens performance.

II. Design

The design of the MOD lens, as well as a traditional parabolic control sample was done using MATLAB. The lens diameter was chosen to be 1 inch, and the focal length was chosen to be 2 inches. The MOD elements were created numerically using MOD lens design equations [4], and the modulation transfer function (MTF) was theoretically predicted for both lens types. These predictions can be seen in Fig. 2 where we observe that the MTF of the MOD harmonic is near diffraction limited as is the MTF at the design wavelength.

We numerically created lenses that focus many THz wavelengths onto a common focal spot. For instance, the lens created for Fig. 2 focuses harmonics spaced every 200 GHz, starting at 200 GHz. The actual height profiles from the lenses are generated in the software (Fig. 1), thus allowing for the fabrication of these lenses.

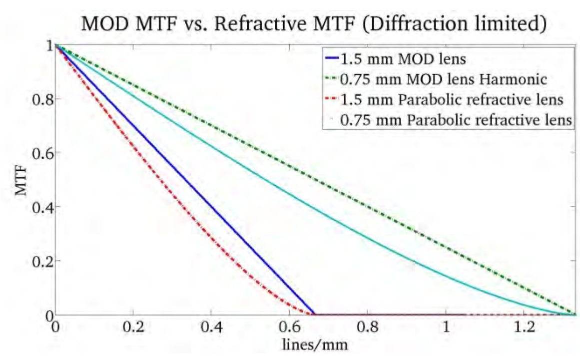

Figure 2. Diffraction limited MOD-lens MTF at design wavelength, and harmonic wavelength, compared to MTF of diffraction limited refractive lenses designed at both wavelengths. The difference in shape can be mostly attributed to the MOD lens being simulated with a square aperture, and the refractive lens having a circular aperture.

III. Fabrication

For the fabrication of the MOD lens, we chose a design with a small number of zones (m in Eq. 1) so they would be physically large enough to machine easily and accurately. To accomplish this and generate a lens with usable harmonic spacing in the THz region we chose a high order (p) along

with a small design wavelength (λ_o). The generated lens had $p = 500$ and $\lambda_o = 3$ µm. This is clearly not a MMW-THz wavelength, but with these parameters inserted into Eq. 1, and the desired focal length, the actual focused wavelength becomes 1.50 mm divided by the zone m. When generating this height profile of the lens the number of zones present is largely dictated by the lens diameter. With a 1 inch diameter there are 4 zones present. Therefore the primary and harmonic wavelengths for the MOD lens are 1.50 mm, 0.750 mm, 0.500 mm, and 0.375 mm, which translate to a very useful frequency range for low-end THz operation (200-800 GHz).

The lens was fabricated in Teflon with a small CNC lathe and can be seen in Fig. 3. With only 4 zones present the smallest Fresnel feature was approximately 2 mm wide and 3 mm tall. We decided to fabricate the lens in Teflon because it exhibits excellent THz transparency and is readily available. Once the CNC turning was complete, the lens was separated from its substrate with a band-saw and polished.

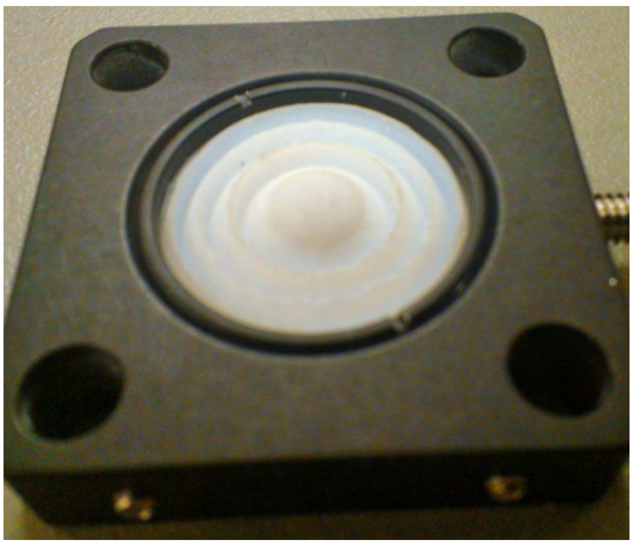

Figure 3. A fabricated MOD THz lens, focusing 200, 400, 600, and 800 GHz.

IV. Results

To test the quality of the diffractive THz lens we conducted knife-edge tests at 600 GHz, which is at one of the harmonic wavelengths (m = 3). The source was a frequency extension module (FEM) driven by a voltage control oscillator (VCO). This source was chopped at 150 Hz, and directed through the lens toward a Schotty-rectifier detector connected through a 30-dB gain low-noise amplifier to a lock-in amplifier. A knife edge was located after the lens and used to find the focal spot.

Once the focal spot was found, the spot size was measured by moving the knife edge perpendicular to the propagation direction until the signal was blocked. A 20 dB drop in signal was considered blocked for this test. The traditional parabolic refractive lens was tested first at 600 GHz to create a baseline and the spot size was found to be ~0.06 inches. Then the MOD lens was tested and the spot size was slightly larger, approximately 0.10 inches. This is likely due to radiation being detected from the out-of-focus harmonics on the lens. Because they are designed for different wavelengths, they will focus on a different spot. When moving the knife edge in, a noticeable drop-off in signal can be seen at 0.05 inches, and then the signal attenuation flattens out. When the blocked signal criterion is 10 dB, the spot size of the diffractive lens is equivalent to the refractive lens, accurate to one one-hundredth of an inch..

A compelling observation during the test is raw signal strength collected. As mentioned in previous work, the diffractive element will absorb less THz radiation because it is thinner [5]. A 3 dB increase in signal strength was observed at the focal point when the MOD lens was focusing the 600 GHz radiation, despite the spot size difference. This means that lenses can be designed to focus carefully chosen wavelengths, with much lower insertion loss.

V. Conclusion

Unlike the limitation in first-order diffractive optics, the MOD lens harmonic focus spacing is selectable as a design parameter. Our results demonstrate this advantage and show imaging performance that is comparable to traditional parabolic refractive lenses at design and harmonic wavelengths. Figure 2 shows that with ideal fabrication conditions the MTF at the design wavelength and its harmonics is nearly diffraction limited. With a height of only 3 mm, focal length of 2 inches, and a diameter of 1 inch this lens is very practical because it significantly reduces the insertion loss. Hence, it could be valuable for combining THz sensor architectures that use multiple wavelengths, and enable more efficient and compact sensor systems.

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